

Design and Capacity Performance Analysis of Wireless Mesh Network



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ABSTRACT

From the network operator's point of view, the high CAPEX/OPEX cost resulting from fixed/wired backhaul links can be inhibitive to successful deployment of broadband wireless services. The emerging wireless mesh network (WMN) technology is seen as one of the potential solutions which may reduce wired backhaul dependency through multihop transmission. Despite the advantages, many remain sceptical on WMN's network capacity and scalability performances particularly when the user density is high. This paper provides an insight on the best possible upper-bound capacity performance of WMN, taking into consideration three key design parameters namely 1) Percentage of wired backhaul points per network, 2) Mesh-to-Access Link-Rate Ratio (R) and 3) Number of radio interfaces per mesh node including hybrid radio options. These design options are compared and contrasted with different deployment densities. The results generally show that the higher the number of backhaul points, the higher the effective access capacity available to mesh node and hence user domain. Increasing the R and the number of radio per mesh node are two alternative means to push up the effective access capacity per mesh node without increasing the number of wired backhaul points. This is most significant in multi radio system where about 80% of the backhaul points can be eliminated with $R=3$ in order to maintain effective access capacity close to full rate (Capacity, $C=1$) per mesh node. It is also found that 50% of the backhaul points can be eliminated with $R=2$ for all radio options (except for the pure single radio case).

Categories and Subject Descriptors

C.2 [Computer Communication Networks]: Network Architecture and Design - *Wireless communication*

General Terms

Performance, Design, Theory and Verification.

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Keywords

Wireless Mesh Networking, Broadband Wireless Access, Network Planning

1. INTRODUCTION

Wireless mesh network (WMN) technology promises cost-effective broadband wireless access solutions especially in places where fixed infrastructures such as DSL or fibre access are limited or expensive. The popularity is largely owed to several key benefits such as low infrastructure cost, easy and fast installation, simplified planning and maintenance.

More recently, WMN has gained significant inroads into municipal deployments such as Wireless Taipei [1], Google Mesh [2], etc. The low start up cost and the usage of unlicensed spectrum has increased its popularity worldwide. Despite the increasing interest, it is not well understood how wireless mesh network will perform under large scale deployment especially when the user density is high e.g. in urban areas. Many remain sceptical on its network throughput and scalability performances.

As discussed in [3], the capacity performance of WMN is generally influenced by a wide range of factors such as MAC protocol, number of radio interfaces per mesh node, number of user domains sharing the same mesh route, co-channel and adjacent channel interferences, routing protocol, network architecture or topology, antenna types, etc. Numerous studies have been carried out to understand the performances and various design parameters from a large scale deployment's perspective [4], [5], [6], etc. However, the performance of a mesh system remains unclear mainly because it depends upon the specific constraints imposed by the factors above and their various combinations and interdependencies. We therefore propose a simplified approach to understand the performance of WMN by analyzing the relationships between three key design options namely 1) the percentage of wired backhaul points, 2) mesh-to-access link-rate ratio (R)¹ and 3) number of radio interfaces per mesh node including hybrid radio options across different deployment densities. Some high-level insights into the best possible upper bound capacity performance of WMN have been established in our earlier work [3]. To better understand the above relationships, this paper extends the analysis to compare and contrast the performance of these design options across a number of selected deployment scenarios in central west London.

¹ ratio of mesh link rate over access link rate (refer figure 1)

This paper is organized as follows: section 2 describes the chain network analysis. Section 3 presents the deployment case study and simulation approach. Section 4 discusses the results and analysis. Finally, the conclusions are drawn in section 5.

2. CHAIN NETWORK ANALYSIS

A detailed analysis on a myriad of design parameters spanning across multiple protocol layers and architectures is beyond the scope of this paper. However, useful high-level insights on the best possible upper bound capacity performance and design options can be appreciated by using the chain analysis results after decomposing a mesh into an equivalent number of logical chains [3]. To obtain such high level insights, it is therefore necessary to assume the following:

- **Fair access capacity.** Each user domain is assumed to enjoy a fair share of its total backhaul point's capacity to ensure a uniform blanket deployment of wireless broadband services. In other words, the access to the wireless medium is assumed to be fairly shared across some fixed timeslots between the user domains and mesh nodes attached to the same backhaul point. This means the mesh access nodes which are further hops away from the gateway enjoy the same bandwidth share as those nodes nearer to the gateway. Various techniques, such as call admission control and fair scheduling [7] have been proposed to make this possible.
- **Negligible RF interferences.** In situation when there are sufficient non-overlapping channels (e.g. in 802.11a) and when there is ideal collision avoidance domain boundary, and/or the operation under licensed spectrum, interference effects resulting from co-channel, adjacent channel, foreign devices, etc, can be significantly reduced. Effects of interferences can also be minimized if smart antenna systems e.g. beam forming are employed between mesh nodes. Such assumptions though practically challenging at this stage, are required in order to obtain an insight on the maximum possible upper-bound capacity limit. This is critical for network operator to obtain an insight on the best possible capacity performance of wireless mesh system and also whether if this technology is only viable under licensed spectrum environment.
- **Perfect routing.** When network dynamic is at statistical equilibrium, a mesh network is assumed to behave like a multihop network. This is assumed that the network is supported by an effective routing scheme.
- **One user domain per mesh access point (MAP).** MAP is an access point with mesh router capability. This means there is only one access link per MAP and it only serves one user domain. All end users within the user domain are sharing the same access point and hence fall under the same collision avoidance zone.

The assumptions are applied to the chain topology as shown in Figure 1. The normalized access capacity of each MAP is analyzed as the number of user domains increases.

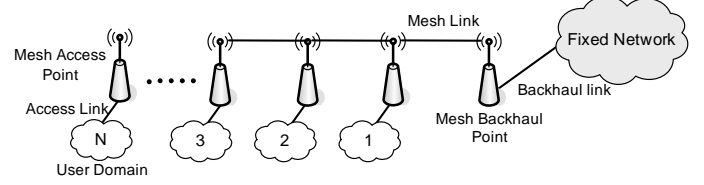


Figure 1. Chain topology with N domains.

Figure 2 shows the theoretical upper-bound capacity performance limit of multi, dual and single-radio chain topology network established from [3] based on the earlier assumptions for a range of different mesh-to-access link rate ratios (R). The normalized access link capacity, $C = 1$ means all the user domains along the chain are able to access their respective access points at full theoretical link rate e.g. at full 11Mbps if IEEE802.11b access is used or 54Mbps in IEEE802.11g/a case.

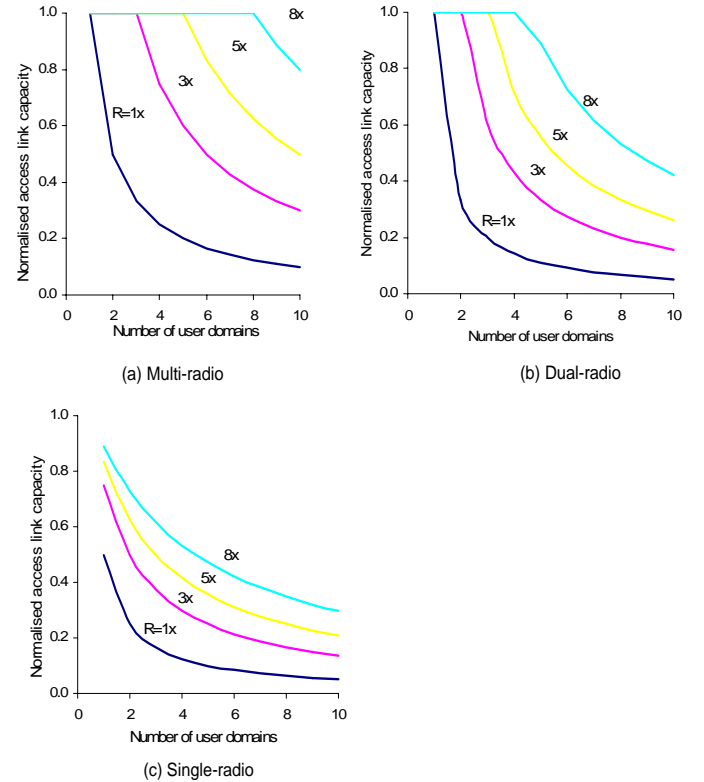


Figure 2. Upper-bound capacity limit of multi-, dual- and single-radio chain topology network.

The plots in Figure 2 can be represented by equation (1) to (3).

Multi radio:

In multiple radio system, each mesh node has multiple radio interfaces. The radio interfaces are normally used to create independent links the neighbouring nodes. In other words a multiradio node can simultaneously transmit (or receive) traffic to each of its neighbours as well as to its own user domain. If the available capacity is shared proportionally by the number of user

domains, the maximum capacity available (in reference to backhaul capacity) to each user domain can be represented by:

$$C = \frac{R}{N} \quad (1)$$

Where: C = Normalized access link capacity
 N = Number of user domains
 R = Mesh-to-Access link rate ratio

Dual Radio:

In this system, each mesh node has two radios — one of which is dedicated for serving access (user domain) traffic and the other for mesh link or mesh backhaul traffic (see figure 1). Since there is only one radio per node for serving the mesh traffic (*access is assumed to be independent of each other), the capacity has to be time-shared between mesh nodes along the multihop chain. In this case each user domain will get:

$$C = \frac{R}{2N - 1} \quad (2)$$

Single Radio:

For single radio system, since there is only one radio in each node, total capacity has to be time-shared between both access and mesh links within the same node as well as across all nodes along the multihop chain. The capacity available to each user domain is therefore the worse than multi and dual radio systems. This can be represented by:

$$C = \frac{1}{1 + \frac{2N - 1}{R}} \quad (3)$$

Practically, the usage of mesh-to-access link rate ratios (R) is relevant to cases where access and mesh backhaul links operate at different rates. This can be due to different modulation and coding schemes or different radio technologies used such as using WiMAX as the mesh backhaul and WiFi as the access.

3. DEPLOYMENT STUDY

In this section, the upper bound capacity limits for different radio systems discussed earlier are applied to some selected deployment scenarios. The main goal is to understand how the effective access capacity per user domain is influenced by the following three key design parameters/options:

- Percentage of wired backhaul points (or MBPs) per network
- Mesh-to-Access Link-Rate Ratio (R)
- Number of radio per mesh node or hybrid radio configuration

The scenarios are divided into three density levels - high, medium and low. This reflects the deployment scenario for urban, suburban and rural zones. Hybrid radio systems are also addressed to understand if there are potential benefits to be gained from using a mixture of radio configurations in the same network.

3.1 Assumptions

For this study, an additional assumption on top of those described in section 2 have been made as follow:

• Uniform link rate

All access and mesh links are optimized to run at uniform link rate with the aid of relay nodes. This assumption reflects a well-planned network whether WLAN or WiMAX where either the distance between mesh or relay nodes falls into the desired Adaptive Modulation and Coding (AMC) region or the antenna gain is boosted to force the link to operate at the a certain desired data rate.

3.2 Simulation Approach

The model was built using MapInfo Pro and Mapbasic [8]. MapInfo is a geographic information system (GIS) software that is commonly used for mapping and geographical analysis. MapBasic is a programming environment within MapInfo. Digital map that supplies physical information of building outlines is used. The SNR of a mesh node to its neighbouring nodes are derived using the following equations. Equation (4) describes the pathloss equation. The Multi-Wall-Floor (MWF) [9] model is given in equation (5). The signal-to-noise ratio (SNR) is computed using equation (6). Other PHY parameters used in the simulation model are listed in Table 1.

$$PL(dB) = -147.6 + 20 \log(f_{rf}) + 10\alpha \log(d) + WallLoss \quad (4)$$

Where: d is distance in meter

f_{rf} is operating frequency band in Hz

α is propagation coefficient

$$WallLoss (dB) = L_s n_s^{\left[\frac{n_s + 5}{n_s + 3} - b \right]} \dots \dots \dots (5)$$

Where: L_s is average loss per wall (12dB)

n_s is number of traversed walls in the direct path

b is a factor (0.5)

$$SNR(dBm) = EIRP - PL - M_{total} + G_{tx} - N_{floor} \dots \dots \dots (6)$$

Where: $EIRP$ is Effective Isotropic Radiated Power

PL is pathloss from equation 4

N_{floor} is receiver noise floor

M_{total} is total margin

G_{tx} is received antenna gain

To facilitate transformation of conventional hotspot type network to mesh, the original single hop access points need to be replaced with Mesh Access Points (MAPs). Every MAP serves a group of end users which is referred as a user domain. Figure 3 illustrates a snapshot of random node distribution reflecting low and high deployment density scenarios in a square km area in central west London.

Table 1. Simulation Parameters (based on typical WiFi 802.11g systems)

Parameters		Notes
Propagation model	Enhanced free space	Enhanced free space model with $\alpha = 2.9$
Operating freq, f_{rf}	2.4GHz	Unlicensed band
EIRP	20dBm	As according to UK's regulation
Rx antenna gain, G_{tx}	7dBi	Typical figure for Omni
Total margin, M_{total}	16dB	Including fading, shadow, interferences
Receiver Noise Floor, N_{floor}	-100 dBm	Assumed 802.11g, noise figure = 5dB
Receiver sensitivity	Ranging from -68 to -88 dBm	Varies according to different modulation schemes. Obtained from WiFi's (802.11g) vendor's specification

The user domains are grouped into clusters, ideally, on the basis of achieving the minimum possible separation distance between adjacent user domains within each cluster. An example of this clustering process for a square km urban environment is shown as shaded regions in Figure 4, where the cluster size is chosen to be uniformly distributed (equal number of MAPs per cluster) so that bandwidth can be evenly/fairly distributed throughout the whole network. The cluster size basically depends on the number of backhaul points available in the network. More MAPs will have to share the same backhaul point if there are less backhaul points in the network. According to [3], the fair bandwidth-sharing assumption used for the chain does not necessarily result in fair sharing within the whole mesh network. In order to achieve that, it is necessary for the user domains to be distributed across the various logical chains in such a way that all of them will operate at the same value of effective access capacity.

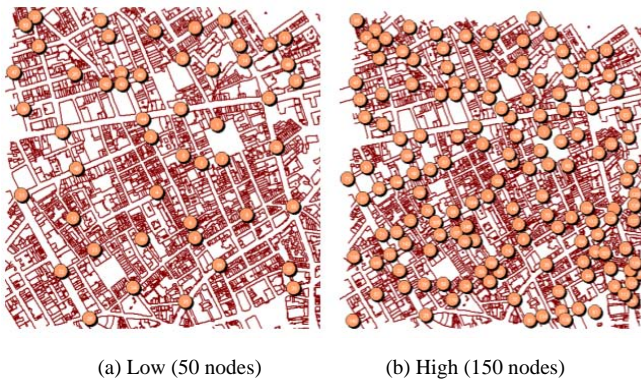


Figure 3. Sample deployment densities (randomly distributed)

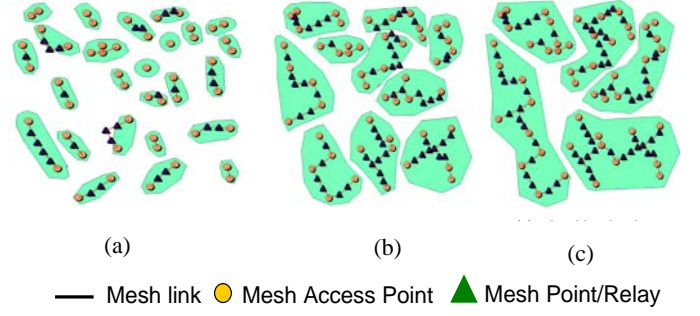


Figure 4. Clustering process with (a) 25, (b) 10 and (c) 5 backhaul points

If the minimum distance between adjacent user domains exceeds the achievable operating range it is assumed that this will be overcome by using an appropriate number of relay nodes. Finally, the most centric node within a cluster is then selected to be the one that will provide access to a fixed line backhaul connection. The location of the node should statistically give the least number of hops for all members of cluster to the fixed line backhaul.

The percentage of backhaul points is defined as the percentage of total number of backhaul points used over the total number of MAPs, which can be represented as:

$$\% \text{ of Backhaul Point} = \frac{\text{TotalMBP}}{\text{TotalMAP}} * 100\% \quad (7)$$

*Note: The relay nodes are not included in this equation as they merely act as signal strength booster and therefore are not affecting the link capacity.

4. RESULTS AND ANALYSIS

4.1 Relationship between Relay Nodes and Backhaul Percentage

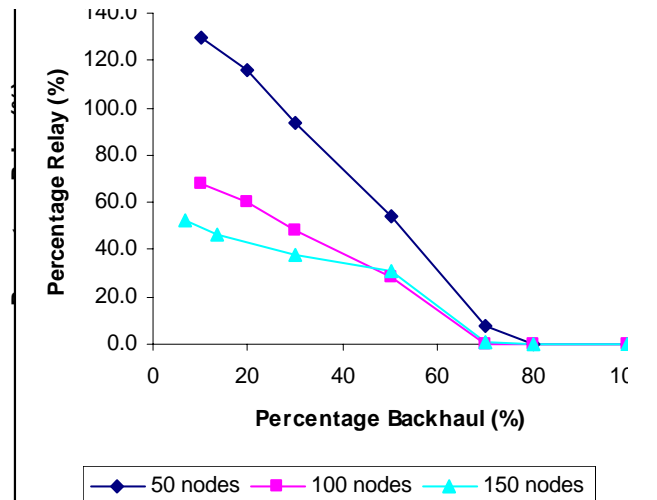


Figure 5. Percentage of relay points (or MPs) vs. percentage of backhaul with different node densities per square km

Figure 5 shows the percentage of relay nodes (or MPs) needed when the percentage of backhaul points varies from 10% to 100%. The percentage of relay nodes is calculated based on (total number of relay nodes/total number of MAPs)*100%. When the percentage of relay nodes exceeds 100%, which means there are more relay nodes than the MAPs in the square km area.

The general trend of the results plotted in Figure 5 shows that decreasing the number of logical links increases the number of relay nodes needed but reduces the number of backhaul points (normally the number of logical links is directly proportional to the number of backhaul points). Consequently, a trade-off exists between the number of relays and backhaul points. For example, providing 10% backhaul points for a 50 node mesh network requires 130% extra relay nodes, whereas this approximately halved if 50% backhaul points are used. Overall, the trade-off decision is very much depending on the cost of provisioning backhaul points against that of providing relay nodes. It can be observed that when there are more than 70% of backhaul points in the area, only a few or no relay nodes needed across the three deployment densities. This is because some smaller clusters can be formed without having to use relay nodes as some of the nodes are already within each others' transmission range. Generally it can also be observed that at backhaul point percentage of 70% or lower, the relationship between backhaul reduction and relay node increment is rather linear. It is also shown in Figure 5 that for a given cluster size, increasing the node density from 100 to 150 per square km reduces the percentage of relays needed by approximately a factor of two.

4.2 Relationship between Number of Radio, Effective Access Capacity and Backhaul Percentage

Figure 6 depicts that the number of radio and radio options used has a significant influence on the effective access capacity per MAP. Multi- indicates pure multi radio system at both chain network and backhaul point. Hybrid dual (or single) is dual (or single) radio system with multi radio backhaul point. Pure dual or single uses all dual or single radio system at both chain network and gateway points respectively.

The results show that, number of radios increases the effective access capacity. For example, when mesh link rate is equal to access rate ($R=1$) for the case of 50 node density pure multi radio system has the best capacity performance as expected. This is followed by hybrid dual, hybrid single, pure dual and pure single as expected. At backhaul percentage 30% or higher, hybrid dual system is performing as good as the multi radio system. This reason is because as backhaul percentage increases, the resulting logical chains will become shorter e.g. to around 1-2 hops. In such situation, both dual radio and multi radio systems can offer the same access capacity per user domain. It is also shown that at 50% backhaul, both multi radio and hybrid-dual systems can offer full access capacity ($C=1$) to all user domains in the network.

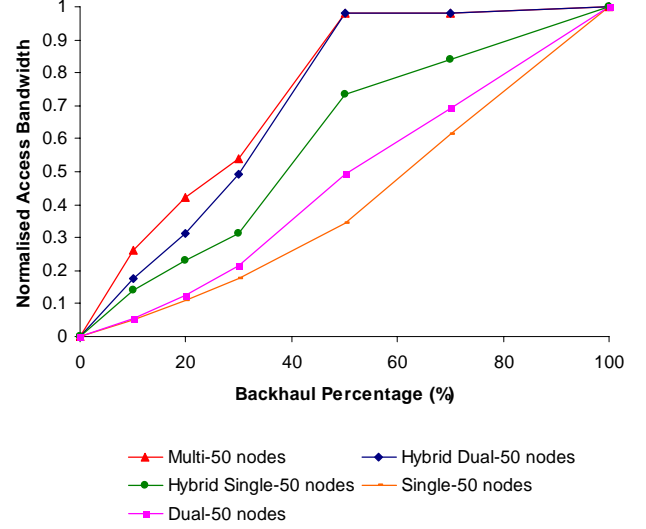


Figure 6. Normalized (or effective) MAP access capacity vs. percentage of backhaul points (50-node case) at $R=1$.

Figure 6 also shows that increasing the number of backhauls points generally increases effective access capacity regardless number of radios per node. For example, in single radio case, effective access capacity, C can be increased to 0.7 by using 70% of backhaul points as compared to 0.1 if 10% backhaul points are used. This also implies that trade off exists between number of radio and number of backhaul points. In other word, if multiple radio mesh node is used instead of single radio, number of backhaul points required to achieve required access capacity will be lesser as compared to single radio.

4.3 Relationship between Effective Access Capacity, C and R

In this section different R values are applied to see their impacts on the effective access capacity per MAP.

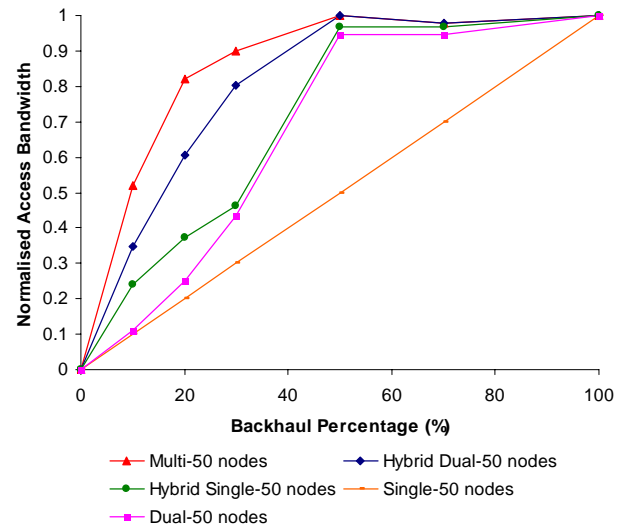
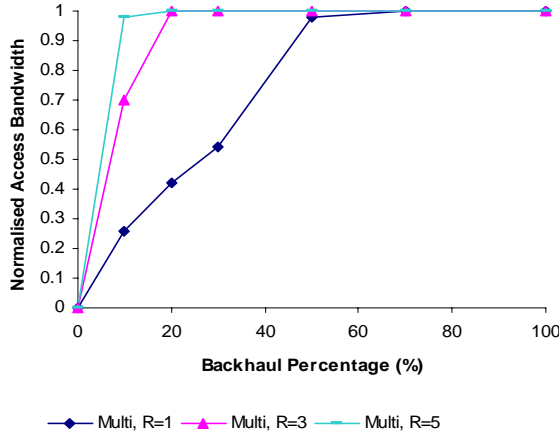


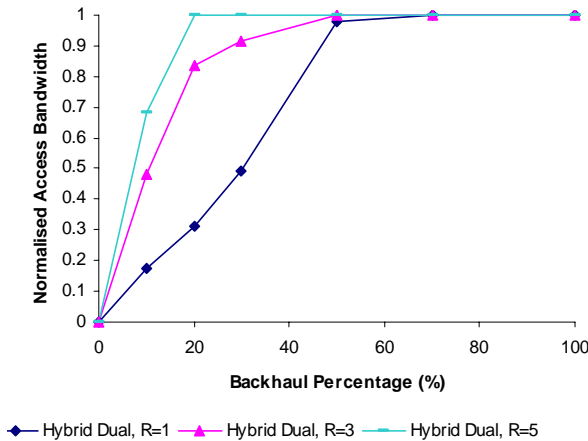
Figure 7. Normalized MAP access capacity vs. percentage of backhaul (50-node case) at $R=2x$

As shown in Figure 7, it can be seen that multi radio, hybrid dual and dual radio systems enjoy greater improvement at higher R values compared hybrid single and pure single. Hybrid single is still superior to dual radio when backhaul is less than 30% at $R=2$. After 30%, both hybrid single and dual radio will have similar performance. The graphs also show that at $R \geq 2$, and when the backhaul percentage exceeds 50%, all radio options except the pure single radio offer close to full effective access capacity to all user domains.

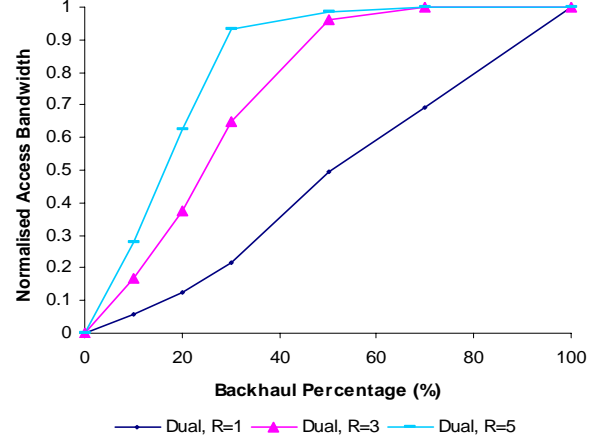
With higher R values, the average MAPs access capacity can be increased significantly with lesser number of backhauls. For example in multi radio case (Figure 8a) it is found that when $R=3$, only about 20% backhaul points are needed in order for each MAP to operate at full access capacity. This is about 80% saving compared to 100% or full backhaul scenario. If $R=5$, only 10% backhaul points are needed. On the other hand, with similar R ($R=5$), 20% backhaul points and 50% backhaul points are required for hybrid dual and pure dual respectively, in order for each MAP in the network to operate close to full capacity.



(a) Multi radio, $R=1, 3$ & 5



(b) Hybrid dual radio, $R=1, 3$ & 5



(c) Pure dual radio, $R=1, 3$ & 5

Figure 8. Normalized MAP access capacity vs. backhaul percentage with varying R and radio options

5. CONCLUSIONS

This paper offered a high-level overview on the best possible upper bound capacity performance of WMN within the context of different percentage of wired backhaul points (MBPs), mesh-to-access link-rate ratio (R) and number of radio interfaces per mesh node including different radio configurations.

Across the three deployment densities (low, medium and high), the number backhaul points is found to be inversely proportional to the number of relay nodes needed. This implies that the reduction of backhaul points has to be traded off with higher number of relay nodes. When there are more than 70% of backhaul points in the area, only a small number relay nodes (none in some cases) are needed across the three deployment densities.

Generally, the higher the percentage of backhaul points, the higher the effective access capacity available to each user domain. Increasing the R and number of radio per MAP are two basic means to push up the effect access capacity per user domain along a chain network. As found in the study, multi radio system gives the best capacity performance followed by hybrid dual, hybrid single, dual and single as expected. With higher R , the effective MAPs access capacity for all radio options can be increased with lesser number of backhaul points. This is most significant in multi radio case where about 80% and 90% of saving in backhaul points with $R=3$ and 5 respectively compared to hotspot scenario. For hybrid dual and hybrid single cases, higher R values are required to save the same amount of backhaul points as in pure multi radio system. It is also found that at 50% backhaul point with $R \geq 2$, all radio options except for the pure single radio case can offer effective access capacity close to full rate ($C=1$).

Such design tradeoffs ultimately depends on cost per bit per users translated from the associated CAPEX/OPEX costs incurred by backhaul point subscription, site rental and maintenance, single, dual or multi radio systems, relays, labour, etc. The detailed economic analysis will be addressed in the future work

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